CONTROLO INTEGRADO DA PRODUÇÃO

MODELAÇÃO E CONTROLO DE SISTEMAS DE PRODUÇÃO

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Programa

1. **Introdução: modelos de manufactura e de serviços**
   Modelos de Sistemas de Manufactura. Modelos de Sistemas na Área dos Serviços.
2. **Planeamento e escalonamento em sistemas de manufactura**
   Planeamento de projectos. Escalonamento de máquinas e escalonamento *job shop*. Escalonamento de sistemas de montagem flexíveis. Escalonamento por lotes. Planeamento e escalonamento em cadeias de abastecimento.
3. **Planeamento e escalonamento na área dos serviços**
   Escalonamento por intervalos, reservas e escalonamento temporal. Escalonamento temporal em desportos e lazer. Planeamento, escalonamento e horários em transportes. Escalonamento de equipas de trabalho.
4. **Desenvolvimento e implementação de sistemas de produção**
   Desenvolvimento e implementação de sistemas. Conceitos avançados em concepção de sistemas. Futuro da área do controlo integrado da produção.

Programa detalhado

1 – Introdução: modelos de manufactura e serviços

- **Introdução**
  - Definição de controlo integrado da produção. Papel e impacto do planeamento e escalonamento em sistemas de produção. Funções do controlo integrado da produção e do planeamento e escalonamento numa empresa.
- **Modelos de Sistemas de Manufactura**
  - Introdução. Trabalhos, máquinas e recursos. Processamento das características e das restrições em sistemas de manufactura. Objectivos e medidas de desempenho.
- **Modelos de Sistemas na Área dos Serviços**
  - Introdução. Actividades e recursos em serviços. Características operacionais e restrições. Objectivos e medidas de desempenho.

Programa detalhado (2)

2 – Planeamento e escalonamento em sistemas de manufactura

- **Planeamento de projectos**
  - Método do Caminho Crítico (CPM). Avaliação do programa e técnica de revisão (PERT). Tempo vs. custo: métodos lineares e não-lineares. Escalonamento de projecto com restrições de equipas de trabalho. Exemplo: sistema de escalonamento de um projecto para a indústria nuclear.
- **Escalonamento de máquinas e escalonamento *job shop***
  - Máquina única e modelo de máquinas paralelas. Programação matemática aplicada a *job shop*. Heurística *shifting bottleneck* para *job shop*. Programação com restrições aplicada a *job shop*. LEKIN: Exemplo de um sistema genérico para escalonamento *job shop*.

Programa detalhado (3)

- **Escalonamento de sistemas de montagem flexíveis**
  - Sequenciação de sistemas de montagem em linhas paralelas. Sequenciação de sistemas de montagem com estações de trabalho. Escalonamento de sistemas de fluxo flexível (*flexible flow shop*) com saltos. Exemplo: modelo misto de sequenciação de montagem na Toyota.
- **Escalonamento por lote**
  - Escalonamento com um tipo de produto. Escalonamentos rotativos com vários tipos de produtos. Escalonamentos arbitrários com vários tipos de produtos. Modelos genéricos de escalonamento por lotes. Exemplo: planeamento e escalonamento de vários produtos na Owens-Corning Fiberglas.
- **Planeamento e escalonamento em cadeias de abastecimento**
  - Definição de cadeia de abastecimento. Configurações possíveis. Métodos de planeamento e escalonamento em cadeias de abastecimento. Modelos de planeamento a médio prazo e a curto prazo para cadeias de abastecimento. Exemplo de implementação na Carlsberg Denmark.

Programa detalhado (4)

3 – Planeamento e escalonamento na área dos serviços

- **Escalonamento por intervalos, reservas e escalonamento temporal**
  - Sistemas de reservas sem folga e com folga. Escalonamento temporal de equipas de trabalho com restrições. Escalonamento temporal com restrições de operadores ou de ferramentas. Exemplo: atribuição de disciplinas a salas na Universidade de Berkeley.
- **Escalonamento temporal em desportos e lazer**
  - Escalonamento temporal em competições desportivas. Escalonamento de competições com programação com restrições e por procura local. Escalonamento de programas televisivos por cabo. Exemplo: escalonamento de uma competição de basquetebol.

Programa detalhado (5)

- **Planeamento, escalonamento e horários em transportes**
  - Escalonamento de frotas. Escalonamento e planeamento de rotas de aeronaves. Horários de comboios. Exemplo: concepção e implementação de sistemas de transporte: Carmen Systems.
- **Escalonamento de equipas de trabalho**
  - Introdução. Escalonamento de dias de folga de trabalhadores. Escalonamento de turnos. Problema de turnos de trabalho cíclicos. Escalonamento de tripulações e equipas de trabalho. Exemplo: escalonamento de operadores num *call center*.

Programa detalhado (6)

4 – Desenvolvimento e implementação de sistemas de produção

- **Desenvolvimento e implementação de sistemas**
  - Arquitectura de sistemas. Bases de dados, bases de objectos e bases de conhecimento. Módulos para gerar planeamentos e escalonamentos. Interfaces com o utilizador e optimização interactiva. Sistemas genéricos e sistemas específicos para uma dada aplicação. Aspectos de implementação e manutenção.
- **Conceitos avançados em concepção de sistemas**
  - Robustez e tomada de decisão reactiva. Mecanismos de aprendizagem. Motores de planeamento e escalonamento, e bibliotecas de algoritmos. Sistemas reconfiguráveis. Planeamento baseado na *web* e sistemas de escalonamento.
- **Futuro da área do controlo integrado da produção**
  - Futuro do planeamento e escalonamento em sistemas de manufactura. Futuro do planeamento e escalonamento em serviços. Métodos de optimização. Desenvolvimento de sistemas.

Bibliografia

- **Pinedo, M., *Scheduling Operations, Manufacturing and Services*, Springer, 2005.**
- Pinedo, M., *Scheduling: Theory, Algorithms, and Systems*, Prentice-Hall Inc., 2002.
- N. Viswanadham, Y. Narahari, *Performance modeling of automated manufacturing systems*, Prentice Hall, 1992.
- M. P. Groover, Automation, *Production Systems and Computer Integrated Manufacturing*, Prentice Hall, 2001.
- R.D. Klafter, T.A. Chmielewski & M. Negin. *Robotic Engineering - An Integrated Approach.* Prentice Hall International, Inc., 1989.

Avaliação de conhecimentos

- Exame (50%) e Projecto (50%)
- Possibilidade de fazer mini-testes ao longo do semestre, dispensando-se de exame.
- **Projecto**: grupos de 2 alunos no máximo (apresentado oralmente).
  - Na célula flexível de produção:
    - http://193.136.103.195/view/index.shtml
  - e/ou em colaboração com indústria / serviços:
    - Planeamento optimizado de produção
    - Simulação de layout de fábrica real

INTRODUCTION

Planning and Scheduling

- Decision-making processes used in many manufacturing and service industries.
- Applied in procurement and production, transportation and distribution, information processing and communication.
- Planning and scheduling rely on **mathematical techniques** and **heuristic methods** to optimize allocation of limited resources to activities.

Example: system installation project

❖ **Example**: Procurement, installation and testing of a large computer system.

❑ **Tasks**: evaluation and selection of hardware, software development, recruitment and training of personnel, system testing and debugging, etc.

❑ **Goal**: complete the project in minimum time, considering the precedence between tasks.

Example: job shop manufacturing

❖ **Example**: semiconductor manufacturing facility.

❑ **Tasks**: wafer fabrication, wafer probe, assembly and final testing (highly specialized manufacturing).

❑ **Goals**: meet as many due dates as possible, while maximizing throughput.

❑ Wafer fabrication consists of several layers, requiring the repetition of operations several times.

❑ Number of orders in the system are usually hundreds and each has its own release date and due date.

Example: flexible assembly system

❖ **Example**: automobile assembly line.

❑ **Tasks**: producing different models, belonging to a small family of cars.

❑ **Goals**: maximizing throughput balancing the workload at each station.

❑ Family of cars can include two-door coupe, four-door sedan and stationwagon.

❑ A bottleneck is the paint shop: color changing is a time consuming process.

Example: production planning

❖ **Example**: production planning in a paper mill.

❑ **Tasks**: Each machine produces various types of paper, characterized by basis weight, grade and color.

❑ **Goals**: maximize throughput, minimizing inventory costs.

❑ Input: wood fiber and pulp. Output: rolls of paper.

❑ Paper machines: 50 to 100 million euros each.

❑ Production plans drawn on an *annual* basis. Cycles of production of 2 weeks.

Example: supply-chain

❖ **Example**: planning an scheduling in a supply-chain.

❑ **Tasks**: material or goods are moved from one facility to another (in a network of facilities).

❑ **Goals**: minimize the total costs (production, transportation and inventory holding costs).

❑ Paper mill is included in a network of production facilities: timberland, paper mills, converting facilities, distribution centers and retailers or end-consumers.

❑ More value is added to the product in each stage of the supply chain.

Example: reservation system

❑ Scheduling problems of a manufacturer are similar to scheduling problems at services (e.g. car rental, hotels)

❖ **Example**: car rental agency.

❑ **Tasks**: decide to provide or not cars to clients. Reservations for very short periods can be denied.

❑ **Goals**: maximize number of days cars are rented out.

❑ Agency maintains a fleet of various types of cars.

Example: scheduling in sports

❖ **Example**: tournament of a soccer (football) league.

- **Tasks**: to schedule the games over a fixed set of rounds.
- **Goals**: to create an ideal schedule that alternates between games at home and games away.
- Some possible constraints:
  - If a city has two teams, in each round one team should play at home and the other team should play away.
  - If two teams are very strong, the other teams should not face these two teams in consecutive rounds.

Example: planning in transportation

❖ **Example**: routing and scheduling of airplanes.

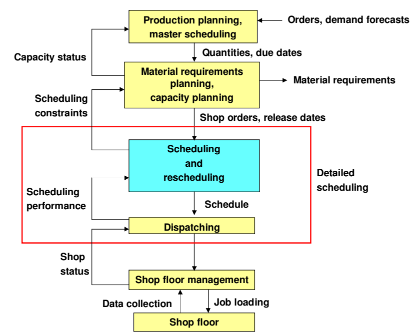
- **Tasks**: estimate profits of assigning a type of aircraft to a flight leg.
- **Goals**: combine the different flight legs into the round trips that can be assigned to airplanes.
- Flight: characterized by **origin**, **destination** and **scheduled departure time**.
- Information with costumer demand for any given flight is available.

Example: scheduling of personnel

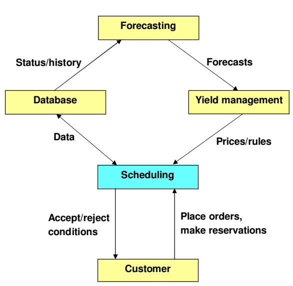
❖ **Example**: scheduling of nurses in a hospital.

- **Goal**: develop shift assignments so that all daily requirement are met and the constraints satisfied at minimal cost.
- Number of nurses required on week days is usually more than on weekends.
- The same happens with day shifts and night shifts.
- State and federal regulations and union rules must may provide additional constraints.

Information flow in manufacturing



Information flow in services



MANUFACTURING MODELS

Manufacturing models

- ❑ In manufacturing models:
  - Resource is called a "**machine**"
  - Task is called as "**job**"
- ❑ A job may be a single operation or a collection of operations to be done in several different machines.
- ❑ There are five classes of manufacturing models, which are described in the following.

Project planning and scheduling

- ❑ Project scheduling is important for large projects
- ❑ A large project consists of a number of jobs with **precedence constraints**.
- ❖ Example: construction of an aircraft, large consulting project.
- ❑ **Goal**: minimize completion time of last job (**makespan**)
- ❑ The **critical path** (set of jobs that determine the makespan) can be identified.

Job shop models

- ❑ Job shop scheduling (include single machine and parallel machine models)

Jobs	Machine Sequence
1	1, 2, 3
2	2, 1, 4, 3
3	1, 2, 4

- ❑ Minimize makespan or the number of late jobs
- ❑ Mostly for make-to-order manufacturing systems
- ❑ Also in services

Flexible Manufacturing Systems

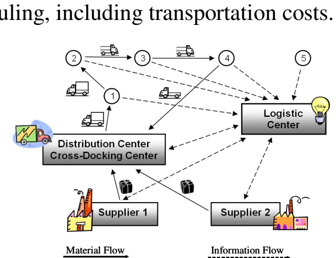
- ❑ Production systems with automated material handling.
- ❑ Material handling or conveyor system controls the movement of jobs and timing of their processing.
- ❑ Mostly for mass production systems.
- ❑ Maximize throughput.
- ❖ **Examples**: automotive industry and consumer electronics industry.

Lot scheduling

- ❑ For medium and long term production planning.
- ❑ Processes are continuous.
- ❑ Switching between products incurs a setup cost.
- ❑ Minimize total inventory and setup costs.
- ❖ **Examples**: process industries, e.g. oil refineries, paper mills.

Supply-chain models

- ❑ In general, are an integration of job-shop and lot scheduling, including transportation costs.



Manufacturing models revisited

- **Discrete models**: project scheduling, job shop or flexible assembly systems.
  - Formulated as an **integer programming** or disjunctive programming.
- **Continuous models**: lot scheduling.
  - Formulated as a **linear or nonlinear programming**

Jobs and machines

- machines $i = 1,\ldots,m$
- jobs $j = 1,\ldots,n$

Static data:

- **Processing time** p_{ij} – processing time of job j on machine i
  - $Q_j = 1/p_j$, machine's production rate of job j
- **Release date** r_j – earliest time at which job j can start its processing
- **Due date** d_j – committed shipping or completion date of job j
- **Weight** w_j – importance of job j relative to the other jobs in the system

Modeling parameters

Dynamic data:

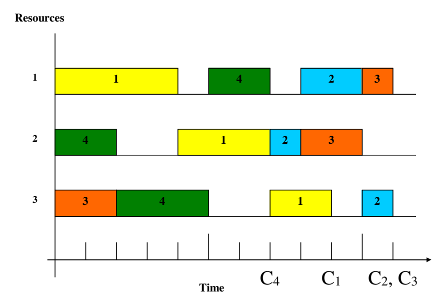
- **Starting time** S_{ij} –time when job j starts its processing on machine i
- **Completion time** C_{ij} – time when job j is completed on machine i

Model representation:

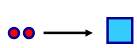
machine configuration | characteristics | objectives

α | β | γ

Completion time

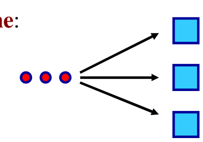


Machine configuration

- **Single machine**: 
- When there is a single **bottleneck** in a multi-machine environment, that bottleneck is scheduled first.
- **Earliest Due Date** (EDD) – orders the jobs in increasing order of their due dates.
  - Minimize maximum lateness among all jobs
- **Short Processing Time first** (SPT) – minimize the average number of jobs waiting for processing.

Machine configuration

- **Parallel machine**:

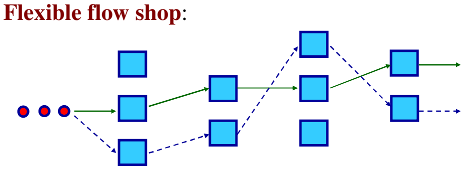


- Machines do **not** have to be identical.
- "Machines" can be old or new, or can be people.

Machine configuration

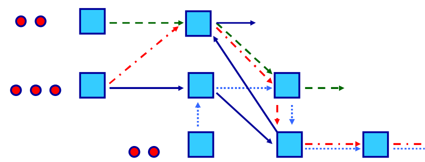
- **Flow shop**:

- **Flexible flow shop**:



Machine configuration

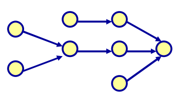
- **Job shop**: (can have recirculation)



- **Flexible job shop** (several machines in parallel)
- **Supply- chain**

Processing characteristics

- **Precedence constraints** – one or more jobs may have to be completed before another job is allowed to start its processing



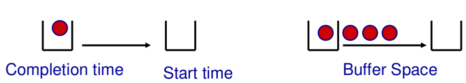
- **Machine eligibility constraints** – in parallel machine environment, M_j denotes the subset of machines that can process job j

Processing characteristics

- **Workforce constraints**
  - workforce consists of several pools
  - each pool consists of operators with a specific skill set
  - number of operators in pool l is denoted by W_l
- **Routing constraints** – specify the operations for each job and the machines at which these operations must be processed.
- **Material handling constraints** – are fixed for automated (e.g., robotized) work centers and adjustable for manual tasks.

Processing characteristics

- **Sequence-dependent setup times and costs**
  - length of setup (reconfiguration or cleaning) depends on jobs
  - s_{ijk}: setup time for processing job k after job j on machine i
  - c_{ijk}: setup costs, e.g. waste of raw material, labor
- **Storage space and waiting time constraints** – amount of space available for Work-In-Progress (WIP) is limited.



Processing characteristics

- **Make-to-Stock and Make-to-Order**
  - D_j – demand rate fixed and constant. Items are produced for inventory and do not have tight dates.
  - Make-to-Order jobs have specific due dates; amount produced is determined by the costumer.
- **Preemptions** – interrupt the processing of a job to process another one with higher priority.
  - Preemptive resume – processing done is not lost
  - Preemptive repeat – processing must be completely repeated
- **Transportation Constraints, etc.**

Performance Measures and Objectives

- **Througput** – is frequently determined by the bottleneck machines, for which the utilization should be maximized.
- **Makespan**

$$C_{\max} = \max(C_1, C_2, \ldots, C_n)$$

  - where C_j is the completion time of job j.
  - Minimizing makespan tends to maximize throughput and balance load.

Performance Measures and Objectives

- **Due date related objectives**
- **Lateness**

$$L_j = C_j - d_j$$

  - where d_j is the due date of job j.
- **Maximum lateness** (minimize worst performance)

$$L_{\max} = \max(L_1, \ldots, L_n)$$

Performance Measures and Objectives

- **Tardiness**

$$T_j = \max(C_j - d_j, 0)$$

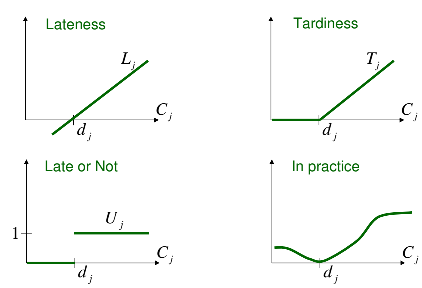
  - Objective function

$$\sum_{j=1}^{n} T_j$$

- **Weighted Tardiness**

$$\sum_{j=1}^{n} w_j T_j$$

Due date related objectives



Performance Measures and Objectives

- **Work-In-Process inventory costs**
  - Minimizing WIP also minimizes *average throughput (lead) time*, which is the time it takes a job to transverse the system.
  - Equivalent to minimize the average number of jobs in the system.
  - Minimizing average throughput time is closely related to minimize the sum of completion times:

$$\sum_{j=1}^{n} C_j \qquad \sum_{j=1}^{n} w_j C_j$$

Others costs and concepts

- **Setup costs**
- **Finished goods inventory costs**
- **Transportation costs**
- In **Just-In-Time** (JIT) concepts, it is important to minimize the **total earliness**.
  - A job should be completed just before its committed shipping, avoiding inventory and handling costs.
- **Robustness**. A schedule is **robust** when the necessary changes in case of disruption (e.g. machine breakdown, rush order) are minimal.

SERVICE MODELS

Introduction

- Impossible to "store" goods
  - It is not possible to "get back" the lost time in a hotel room.
- Resource availability (e.g. people, rooms or trucks) often varies
  - May even be part of the objective function
- Saying "no" to a customer is common
  - "No available seats on that flight" (even if there are some!)
  - Try to book a restaurant for 8 or 9 PM

Reservation systems and timetabling

- **Reservation systems**
  - A job j has a **duration** p_j and the starting and completion times are usually fixed in advance.
  - **Example**: in a car rental agency, a job is the reservation of a car for a given period.
- **Timetabling (rostering)**
  - A job or activity j with a duration p_j, which has to be scheduled in a time window in the interval:

  [**earliest possible starting time** r_j, **latest possible completion time** d_j]
  - **Examples**: exam scheduling, scheduling operating rooms

Service models

- **Tournament scheduling and broadcast television models**
  - Tournament scheduling – *parallel machine* problem, where all the jobs have the same processing time.
- **Transportation scheduling**
  - **Examples**: airlines, railroads, shipping.
  - **Job** – trip or flight leg; **machine** – ship, plane or vehicle.
  - Trip k incurs a cost c_k and generates a profit π_k.
  - Objective: minimize total cost or maximize total profit.

Workforce scheduling

- **Shift scheduling** in service facilities
- **Example**: call center
  - Time interval i requires a staffing of b_i (integer).
  - Objective: minimize total cost.
- **Crew scheduling** in transportation.
  - Depends on the specific tasks to be done
  - Crew scheduling is often intertwined with other schedules (e.g. routing and scheduling of planes or trucks).

Activities

- **Examples of activities**:
  - meetings to be attended by certain people
  - game to be played by 2 teams
  - flight leg to be covered by a plane
  - personnel position to be occupied in a given time period
- **Data**:
  - duration → processing time p_{ij}
  - earliest possible start time → release time r_j
  - latest possible finishing time → due date d_j
  - priority level → weight w_j

Resources

- **_Machines_**: classroom, hotel, rental car, stadium, operating room, plane, ship, airport gate, dock, railroad track, person (nurse/pilot)
- *Synchronization* of resources may be important
  - Need a plane and a pilot
  - Classroom, video projector equipment, professor, students
- Characteristics of resources
  - Classroom: capacity, equipment, cost, accessibility.
  - Truck: capacity, refrigeration, speed
  - Person: specialist (surgeon, nurse) with skills (languages)

Operational characteristics

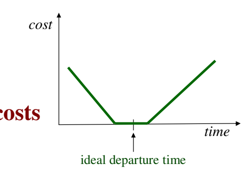
- **Time windows** (release dates and due dates)
- **Capacity requirements and constraints**
- **Preemptions** – many activities are difficult to preempt (e.g. operations flight leg or game).
- **Setup times and turnaround times**
  - Setups between consecutive meetings or trips.
  - ❖**Example**: Runway in an airport is a resource, takeoff and landing are activities. Necessary idle time between activities.

Operational characteristics

- **Operator and tooling requirements**
- **Workforce scheduling constraints**
  - Shift patterns, break requirements
  - Union and safety rules

Objectives

- Combination of two types of objectives: one concerning the *timings* and other concerning the *utilization of resources*.
- General objective: minimize the total cost of all the assignments.
- **Makespan**
- **Setup costs**
- **Earliness and Tardiness costs**
- **Personnel costs**



Computational complexity

- Easy problems:
  - Sort n numbers
  - Solve a system of linear equations
- **Hard** problems:
  - Schedule a factory, deliver packages, schedule buses, …

Computational complexity

- $f(n)$: the number of "basic operations" needed to solve the problem with input size n
- Easy: $f(n)$ is polynomial in n
  - $\mathcal{O}(n)$, $\mathcal{O}(n \log n)$, $\mathcal{O}(n^2)$, …
- Hard: $f(n)$ is exponential in n
  - $\mathcal{O}(2^n)$, …

Hard vs Easy

$\mathcal{O}(n)$	$\mathcal{O}(n \log n)$	$\mathcal{O}(n^2)$	$\mathcal{O}(2^n)$
1	0	1	2
10	10	100	1024
20	26	400	
50	85	2500	
100	200	10000	
1000	3000	1,000,000	

Hard vs Easy

$\mathcal{O}(n)$	$\mathcal{O}(n \log n)$	$\mathcal{O}(n^2)$	$\mathcal{O}(2^n)$
1	0	1	2
10	10	100	1024
20	26	400	1048576
50	85	2500	1,125,899,906,842,624
100	200	10000	
1000	3000	1,000,000	

Hard vs Easy

$\mathcal{O}(n)$	$\mathcal{O}(n \log n)$	$\mathcal{O}(n^2)$	$\mathcal{O}(2^n)$
1	0	1	2
10	10	100	1024
20	26	400	1048576
50	85	2500	1,125,899,906,842,624
100	200	10000	1.268×10^{30}
1000	3000	1,000,000	1.072×10^{301}

Hard vs Easy

- 10^{301} operations required in worst case
- Age of universe: 10^{18} seconds
- Fastest Computer today: 10^{14} op/sec
- If it is going to take 10^{250} times the age of the universe to schedule a factory?
  - *May be it is possible to do it in a reasonable time in most cases!*
  - *May be a good (but not the best) solution can be obtained in a reasonable amount of time!*

P and NP problems

- The efficiency of an algorithm is measured by the maximum (worst-case) number of computational steps needed to obtain an optimal solution.
- Problems which have a known **polynomial** algorithm are said to be in **class P**; the effort of the algorithm is bounded by a polynomial function of the size of the problem.
- For **NP** (**non-deterministic polynomial problems**) no simple algorithm yields optimal solutions in a limited amount of computer time.